AFRL-RQ-WP-TM-2013-0134

AIR VEHICLE INTEGRATION AND TECHNOLOGY RESEARCH (AVIATR)

Task Order 0003: Condition-Based Maintenance Plus Structural Integrity (CBM+SI) Demonstration

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The Boeing Company

MARCH 2010
Interim Report

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YY)*
March 2010

2. REPORT TYPE
Interim

3. DATES COVERED *(From - To)*
01 September 2009 – 31 March 2010

4. TITLE AND SUBTITLE
AIR VEHICLE INTEGRATION AND TECHNOLOGY RESEARCH (AVIATR)
Task Order 0003: Condition-Based Maintenance Plus Structural Integrity (CBM+SI) Demonstration

5a. CONTRACT NUMBER
FA8650-08-D-3857-0003

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
62201F

6. AUTHOR(S)
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5d. PROJECT NUMBER
2401

5e. TASK NUMBER
N/A

5f. WORK UNIT NUMBER
Q07G

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory
Aerospace Systems Directorate
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Air Force Materiel Command
United States Air Force

10. SPONSORING/MONITORING AGENCY ACRONYM(S)
AFRL/RQVS

11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S)
AFRL-RQ-WP-TM-2013-0134

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES
PA Case Number: 88ABW-2013-1894; Clearance Date: 19 Apr 2013. This report contains color.

14. ABSTRACT
This report summarizes recent progress made on the AVIATR contract Task Order 3, Condition Based Maintenance plus Structural Integrity – Basic Phase. Similar to previous progress reports for this project the organization of the report follows the Work Breakdown Structure, and specifically documents the progress during the current reporting period, September 2009 through March 2010 on the Demonstration task (WBS 1.1.2).

15. SUBJECT TERMS
structural reliability, cost-benefit analysis, maintenance scheduling

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT:	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON (Monitor) / 19b. TELEPHONE NUMBER *(Include Area Code)*
Unclassified	Unclassified	Unclassified	SAR	40	Eric J. Tuegel / N/A

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Summary of March Bi-Annual Report

This report summarizes recent progress made on the AVIATR contract Task Order 3, Condition Based Maintenance plus Structural Integrity – Basic Phase. Similar to previous progress reports for this project the organization of the report follows the Work Breakdown Structure, and specifically documents the progress during the current reporting period, September 2009 through March 2010 on the Demonstration task (WBS 1.1.2) which contains the following key sub-sections:

1.1.2 Demonstration
- 1.1.2.1 ASIP Integration
- 1.1.2.2 SHM Analysis
- 1.1.2.3 Data Analysis
- 1.1.2.4 Sensitivity Analysis
- 1.1.2.5 Measurement for Success
- 1.1.2.6 Forward Looking Assessment

This document provides an update to the progress on this project during the current reporting period. The focus of the August progress report was on nearly all remaining elements of the Strategy Development task. The remaining elements of the Strategy Development task which concluded in September were presented at the face to face meeting held in December at the Boeing facility in Seal Beach, CA. A complete written report of the Strategy Development will be presented in the final report for this project.

Due to funding issues, the Demonstration task scheduled to start in October 2009 was not fully implemented until January 2010. The level of effort on the beginning tasks including: ASIP Integration, SHM Integration, and Data Analysis have been increased to meet the original schedule. In addition, the Measurement for Success task has been initiated much earlier than originally planned, as it became clear that there were critical questions to be asked in developing the baseline and alternative models that would be very beneficial to the detailed implementation of the strategy than leaving the development of these cost models toward the end of the program.

The progress in each of the tasks is documented in detail in the following sections, for simplicity the sections are numbered according to the fourth level of the WBS structure (1.1.2.x, where x is 1 through 6). The Sensitivity Analysis and Forward Looking Assessment tasks have not started yet and are scheduled to begin in August and be completed in September.

The Demonstration phase is planned to be completed on schedule with the delivery of the project final report at the end of October. At the present time, there are no major issues to report. The project is expected to be completed on schedule and on budget.

1.0 ASIP Integration

The focus of this task is to provide technical oversight of the application of the Strategy Development completed previously to the F-15 FS 626 Bulkhead structure demonstration. While providing direction and oversight, the key focus is the coordination of the three principle tasks, SHM Integration, Risk Analysis (Data and Sensitivity Analysis tasks) and Measurement for Success (business case development), while keeping a record of indentified technology gaps and challenges.

This task runs the duration of the Demonstration Phase, and is key to coordinating the flow and gathering of information between the principle tasks, as well as obtaining the necessary information from the F-15 program and maintenance facilities, and our leverage projects.

Two key leverage projects have been identified and discussed from the beginning of the project. They are the Structural Health Monitoring (SHM)/Assessment for Bonded Repairs program, discussed briefly in Section 2 SHM Data Integration, and the F-15 program which has provided all of the detailed FEM and crack growth analyses, and maintenance information on the bulkhead component.

In addition to the technical oversight and information coordination, the ASIP Integration task is looking at how, so called, actual usage data, in coordination with initial and updated design usage spectrum data can be used to develop a method to estimate, i.e. predict, future usage. The initial data for this task has been obtained from the F-15 program. The basic approach is to start with the initial assumed design usage data and apply Bayesian updating techniques to obtain a continuously evolving forward looking usage spectrum. In the early stages of service the estimated usage will be “weighted” toward the design spectrum. As the aircraft accumulates flight hours and ages the weight in the composite usage spectrum will gradually shift toward the demonstrated usage. The assumption being, without other influences, that as the aircraft reaches retirement (here defined not as the design flight hours at retirement, but rather in a risk based approach where the cost of continuing to maintain the prescribed level of risk exceeds an acceptable cost value) it is more likely that the aircraft will continue to see service similar to what it has experienced in the past, while still maintaining some portion of the initial, or updated, design spectrum. This analysis is expected to be completed in May and incorporated into the Risk/Sensitivity Analysis, as well as, Measurement for Success tasks.

2.0 SHM Data Integration

The focus of this task is to provide SHM system information to the CBM+ architecture under evaluation. To do this, Boeing is using the Boeing/AFRL SHM Design Framework along with the specific F-15 626 bulkhead SHM system requirements developed previously for this effort. Using the SHM Design Framework for selecting appropriate SHM technologies and methods provides a structured method for choosing appropriate technologies to meet SHM data requirements. Candidate technologies (addressed as system-level solutions) are traded against requirements, concept of operations and costs (when available). Tasks completed during this reporting period focused on 1) continuing to integrate and evolve the design of the SHM system with the proposed risk-based analysis process (directly aiding the Data Analysis and Prediction tasks), and 2) providing SHM system concept of operations (CONOPs) inputs, development cost estimates, and hardware cost estimates to support the Measurement of Success via Technical Performance Measurements (TPMs) tasks.

2.1 SHM System Design for Inclusion with the Risk-Based Analysis Process

The basic requirements for the SHM system is that it must: 1) retrofit existing vehicles, 2) be a self contained system, 3) detect cracks before they are visible (i.e., before they extend beyond structural buildups that require disassembly for visual detection), 4) be relatively easy to install, and 5) be capable of withstanding all of the operational environments the host structure must withstand (e.g., debris, fluids, temperature extremes, etc.). In addition, qualifying systems must be capable of meeting or exceeding the minimum detectible crack size and Probability of Detection (POD) required by the proposed risk-based analysis process. For the two bulkhead crack locations (i.e., bulkhead lower flange aft edge crack 237 location and bulkhead aft center fuselage FS 629.90 12B location), several monitoring technologies were considered including: Comparative Vacuum Monitoring (CVM), Smart Washers, Crack Wires, Piezoelectric Ultrasonic Arrays, Fiber Optic Strain Sensing, and Acoustic Emission Systems.

The fact that the cracks are considered "hidden" in built-up structure removes the possibility of CVM, smart washer and crack wire solutions. While the total system costs are being evaluated as part of this effort and are not yet fully defined, it was assumed that systems that require active monitoring during flight would be cost prohibitive (due to additional complexity, weight, qualification requirements, and potential inclusion with existing on-board data systems) and thus fiber optic and acoustic emission options were dropped. The remaining technology capable of meeting all of the system level requirements is the piezoelectric solution (note that it must still be shown that the piezoelectric solution does, in fact, meet the minimum detectible crack size and POD requirements).

A notional arrangement of piezoelectric sensors/actuators to detect cracks at the 237 and 12B locations is depicted in Figure 1. Two initial options were proposed and used in the initial risk approach process evaluation for a system that includes SHM, namely:

1. Single zone: one detectable crack size with probability of detection 100% (or a specified POD)
2. Multiple zones: several detectable crack sizes with corresponding probability of detection for each crack size. The largest one will be the same as the single zone case, i.e., 100% (or a specified POD).

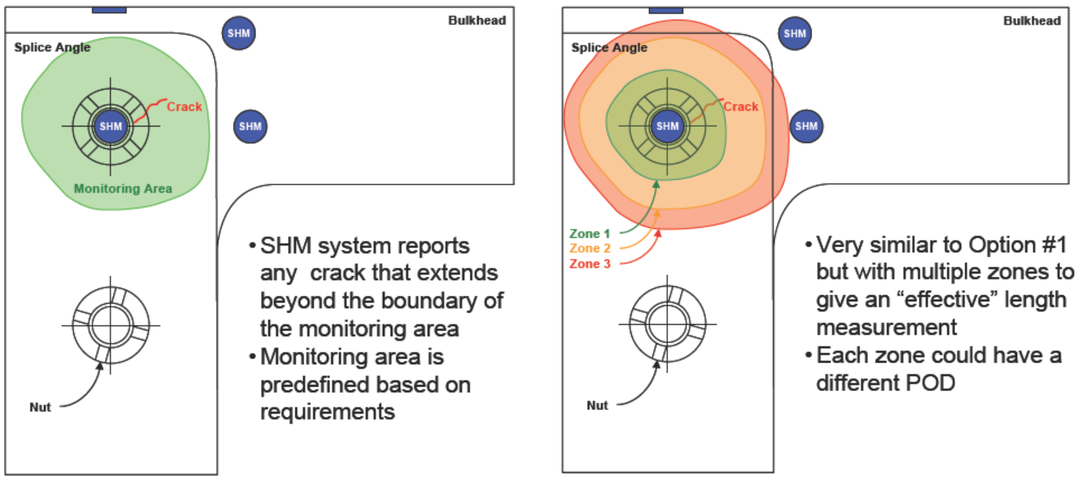


Figure 1. Boolean Type of SHM – Single Zone and Multiple Zones

Note that the detailed SHM system design for the items listed above is being considered under the U.S. Air Force Research Laboratory Structural Health Monitoring (SHM)/Assessment for Bonded Repairs program (F33615-03-2-3300). With respect to using the SHM Design Framework, critical design trade parameters include:

- Actuation authority sensitivity – how to make sure ultrasonic energy is propagating deep enough into the built-up structure and traveling far enough to be observed by the sensors
- Sensor topology – how to optimize sensor number and placement to maximize sensitivity to ultrasonic energy scattered or reflected by the flaw/damage of interest
- Input signal source optimization – how to determine the correct waveform(s) to input to the structure that will be most sensitive to flaws/damage and detectible by the sensors
- Algorithm development – how to process the sensor data to produce the most accurate and reliable flaw/damage size estimates

This AVIATR CBM+SI effort is complimenting that effort (and vice versa) by working to address the specific minimum detectible crack size and POD requirements (described in Section 3), as well as developing the proper methods for modeling, estimating and quantifying SHM derived PODs and their respective reliabilities. As the SHM system design matures, so will the PODs for use in the risk assessment studies.

2.2 SHM System CONOPs, Costs and Contribution to TPMs

During the current reporting period, SHM system information was collected to support the definition of concept of operations, development cost estimates, and hardware cost estimates to support the Measurement of Success via Technical Performance Measurements (TPMs) tasks. This information is summarized in Section 3.2 "Perform Analysis to Model Identified Uncertainties" and Section 5 "Measurement of Success via Technical Performance Measurements (TPM)".

2.3 Next Steps

The remainder of the SHM Integration effort will focus on methods for estimating the performance of the proposed SHM system, specifically on estimating PODs for the 237 and 12B locations. Doing this will require developing models to relate the actual flaw size to the predicted flaw size, understanding and expressing this information with respect to critical flaw sizes, and finally developing estimated POD functions to be used in refined risk assessment evaluations. In addition, this part of the overall effort will continue to refine the approach for integrating the SHM data into the CBM+ architecture based on the CBM+SI requirements as well as how the data are provided to the overall maintenance process.

3.0 Data Analysis and Prediction

The objective of this task is to apply the developed strategy and develop risk assessment approaches (tasks 1.1.2.3 and 1.1.2.4) integrated into a CBM+SI framework. The premise is that formulating a risk based approach will provide benefits by reducing the overall maintenance cost and improving the aircraft's availability. The approaches will be demonstrated by solving the proposed beta test cases.

Through the application of the developed strategy in this demonstration, it is expected that the strategy will be updated and improved as relevant information and issues arise. Specifically, through the Demonstration, key elements for the Strategy Development will be continuously re-evaluated. From this demonstration phase experience, continue to improve the proposed CBM+SI strategy:

- Assess that the requirements are sufficient
- Assess that the architecture prototype is suitable
- Assess that the proposed data flow is accurate and easily applied
- Remove technology gaps and shortcomings from the experience gained, as appropriate, and identify and document others which are outside the scope of this project.

3.1 Collect Data Required for ASIP Reliability and Risk Analysis

The first step in this task was to determine the required data based on the Strategy Development tasks, Requirements (WBS 1.1.1.1) and Architecture Prototype (WBS 1.1.1.2) for ASIP reliability and risk analysis.

The data required for ASIP reliability and risk analysis are: on-board SHM data, Non-destructive Inspection (NDI) data, deterministic crack growth analyses data, full-scale testing results, maintenance experience or repair quality, material strength, individual aircraft tracking data (i.e., load exceedance data), initial quality flaw, failure report, life cycle cost data, and maintenance hours before and after using the proposed information tools (e.g., IETM), etc.

The data collection was coordinated with the following parallel tasks, ASIP Integration, SHM Integration, and TPM Measurement of Success.

Data have been collected for two F-15 Bulkhead critical locations, 12B (cracks emanating from a series of 18 bolt holes) and 237 (cracks which develop in the built-up interface section of the lower flange on the bulkhead). How these data are being used to model the constituent random variables in the reliability and risk analysis will be discussed in the following subsections.

3.2 Perform Analysis to Model Identified Uncertainties

In the Strategy Development phase the Architecture Prototype task evaluated the current ASIP risk assessment process to determine the requirements for modeling uncertainty, and that analysis is implemented in this section, with the exception of SHM data which is discussed below.

Details on how to model the collected uncertainty data into random variables has been summarized in the August 2009 progress report. In addition the requirements for structural health monitoring data requirements was also detailed in that report, and referenced here. Based on the above, a summary of all input data, excluding SHM data which is discussed below, for the Bulkhead component's 12B location can be seen in the Appendix A at the

end of this report. Uncertainty modeling associated with SHM data is coordinated with the SHM Integration task considering two proposed approaches of a single or multiple zone SHM probability of detection (POD) capability.

As discussed in the Strategy Development: Requirements task, two bookends of SHM capability have been proposed. First, at the limited capability end a Boolean approach, this would give limited binomial crack detection information within the monitoring area and second, a high capability approach that would be able to determine crack length and orientation with high confidence. However, with project constraints, only the SHM – modified Boolean approach considering single and multiple zones will be developed and demonstrated as shown in Figure 1. The SHM – high fidelity system will not be able to be developed.

For the Boolean type of SHM, we have the following definitions:

1. Single zone: one detectable crack size with probability of detection 100% (or a specified POD, and confidence)
2. Multiple zones: several detectable crack size zones with corresponding probability of detection for each zone. The largest one will be the same as the single zone case, i.e., 100% (or a specified POD, and confidence). For the other crack size zones, the probability of detection may be different.

Based on the above definitions, crack size criteria data were determined based on the F-15 program requirements and experience for the two locations under consideration (12B, bolt holes, and 237, built-up section) at the FS 626 Bulkhead area:

1. For 12B (bolt holes):
    a. 0.03 inches – easy to repair by drilling out the hole to the next oversize level. When crack is smaller than 0.03", the maintenance authority is instructed to use the next oversize fastener.
    b. 0.05 inches – Bolt hole eddy current NDI's capability. When crack is smaller than 0.06" but larger than 0.03", the maintenance authority is instructed to use the Force-Tec system. A Force-Tec is a thick walled bushing, cold worked into place.
    c. 0.12 inches – this crack size is still repairable by using Force-Tec technology. The actual repairable size is up to 0.18 inches (double the size of the holes). When the crack is between 0.06 in. and 0.18 in., engineering may instruct maintenance personnel to "pull" the hole off center to help cover the crack. An issue is that the manuals do not allow the typical maintenance crew to do this and additional engineering support is required.
    d. 0.18 – critical crack length. When the crack is larger than 0.18", a replacement of the BH is the only solution currently available. A potential repair strategy is currently in development stage by the F-15 program for this large crack size. However, the cost of repair for the large crack like this is expected to be much more costly than the previous three stages.
2. For 237 (built-up section along flange)
    a. 0.03 inches – easy to repair by blending
    b. 0.05 inches – Limit of ultrasonic NDI inspection capability for fillet radii inspection

   c. 0.1 – considered repairable by F-15 program; repair technique in development.
   d. 0.3 – crack growth analysis critical crack length
3. Note that for the bolt hold location (12B) 235.6 hours are required to grow the crack from 0.12 inches to 0.18 inches. Considering the built-up flange section (237) 1429 hours is required to grow the crack from 0.1 inches to the critical crack size of 0.3 inches. Therefore, the size for the single zone Boolean SHM is 0.12 inches and 0.1 inches for 12B and 237 locations respectively. Their corresponding probability of detection will be determined as part of the SHM Integration task and documented in a subsequent report.

The other key data required is how much time is required for the repair process. Based on the above definitions the following information was provided by the F-15 program:

Zone 12B: 18 holes (7-8 incidents reported)

1. Assume plane is open and inspected, and crack was found
   a. When crack is smaller than 0.03" – 30 minutes to repair
   b. When crack is smaller than 0.06" but larger than 0.03" – 30 minutes to repair
   c. When crack is smaller than 0.18" but larger than 0.06" – 1.5 hours to repair
   d. When crack is larger than 0.18" – replace bulkhead
      i. The F-15 program is working on an alternate repair approach. The approach is expected to be completed in July, and the program anticipates a 1000 - 1500 labor hours repair time frame.

Zone 237: 2 fillet radius (2 incidents reported)

1. Assume plane is open and inspected, and crack was found
   a. When crack is smaller than 0.03"– 30-60 minutes to repair
   b. When crack is smaller than 0.1" but larger than 0.03" – 30-60 minutes to repair
   c. When crack is smaller than 0.3" but larger than 0.1" – possible plane killer
      i. The F-15 program is working on a repair approach. The approach is expected to be in the 1000 - 1500 labor hours repair time frame.
   d. When crack is larger than 0.3" – replace bulkhead

In addition to the crack size for detection, it is important to understand the data collection time requirements for both NDI and SHM approaches.

1. For NDI inspection, to access the bulkhead and perform the inspection, it takes around 2-3 hours, based on information from F-15 program maintenance records.
2. For SHM inspection, since this is a retro-fit application, all data acquisition hardware and software will be off-board in order to mitigate any weight or system penalties – weight neutral target. The information provided below is based on experience from the SHM community of experts.
   a. Data collection will involve bringing a portable system to the aircraft consisting of a computer, data acquisition hardware and power supply. Options to this include adapting a system to fit in/on an existing maintenance "rack" or system and to have external power supplied. The data collection

system will provide power to the onboard sensors and collect the data from the sensors. In general, a "source" actuator will introduce ultrasonic energy into the structure and one or more sensors will pick up the transmitted energy. The data acquisition hardware will collect the data picked up by the sensors and will store it. Once connected and powered up, the actual collection of data should take no more than 5 or 10 minutes and is completely automated (most likely an executable with a "start" button on it).

b. Data processing takes the stored data from the sensors and turns it into useful information. Based on the capability desired, the information will be Boolean (i.e., "exceeds" or "does not exceed" for a specific zone) or detailed crack information (crack specifics like orientation, length, etc.).

c. Data transfer is the process of moving the crack information to a location/computer that will be performing the CBM+SI analysis. Theoretically, this could happen in several different ways ranging from data entered in a maintenance log by the technician who ran the data acquisition process and data collection routine to an uploaded data file (via thumb drive, or Ethernet, etc.) sent back to cognizant engineers for analysis.

The proposed risk assessment analysis must be able to integrate the SHM information and its related uncertainties. In addition, based on the inspection and repair data collected, it is important to determine the optimal maintenance schedule using the risk-based approach with consideration of both NDI and SHM. For the purposes of this report and to facilitate the demonstration of the incorporation of SHM data into the approach, the assumption is made that the SHM system has the same capability as that of existing NDI technology. The SHM Integration task will develop a POD data set to be used in future analysis and business case assessments. Based on this assumption, it is possible to perform current risk assessment analysis process, an updated analysis process with the addition of SHM, and then a risk-based optimization process and code to identify the optimal maintenance schedule with considering of both NDI and SHM. These preliminary and exploratory results will be shown in the following sections.

3.3 Implement Proposed Risk-based Methodology And Develop Code

Step 1. Based on Strategy Development proposed data flow (subtask 1.1.1.3), implement proposed risk-based methodology and develop code to incorporate SHM data obtained from task 1.1.2.2 (SHM)

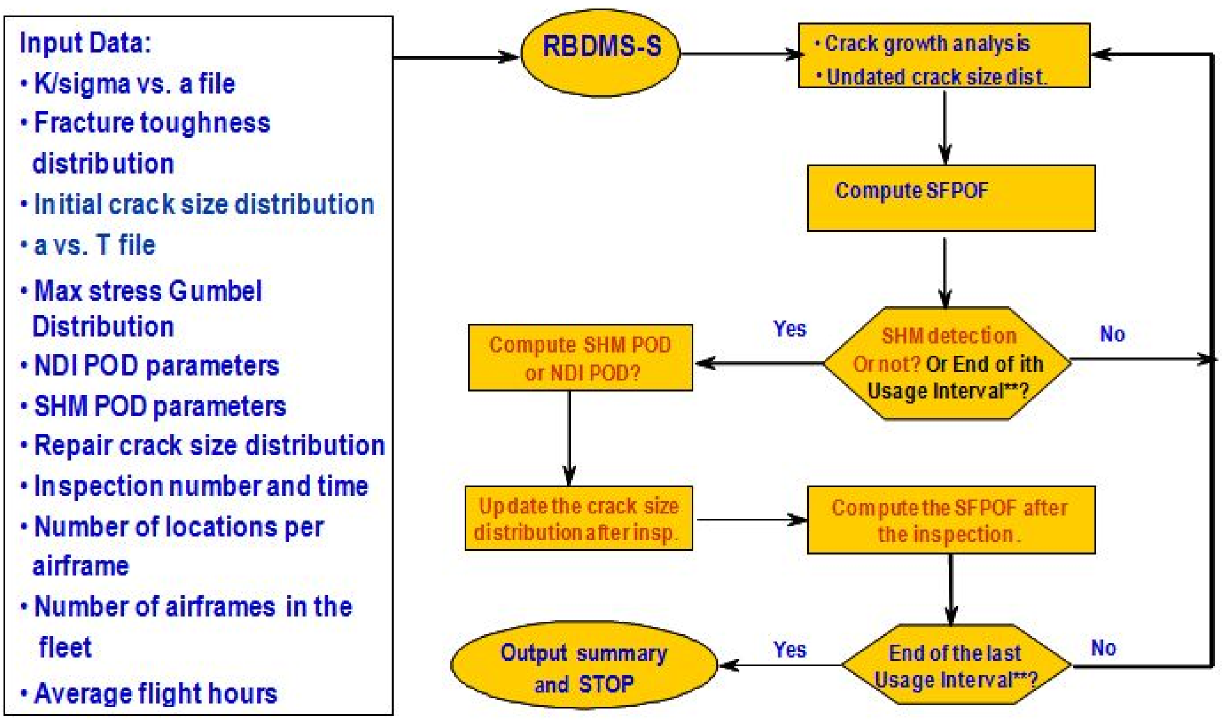
The purpose of this task is to implement the proposed risk-based methodology and develop the necessary code to calculate the risk with consideration of SHM data and to determine logistic or maintenance action needs. In the following, the methodology part has been defined and discussed; however, the code portion will not be fully developed until the late April or early May timeframe.

The proposed risk-based analysis process with addition of SHM is discussed below.

1. With the addition of SHM, the current risk assessment process will not be changed but it may increase the analysis iterations as shown in Figure 2. When there are no cracks found by SHM before the end of selected inspection interval, which shall be determined by using

the original risk assessment process based on the 1.E-7 risk requirement without considering the SHM capability, an NDI inspection will be performed as usual. However, when a crack is found before the end of inspection interval, it is important to determine the impact of SHM. To perform the above analysis, the following information shall be required:

a. Input data requirements (1. Aircraft usage characterization, 2. Crack growth and residual strength based on demonstrated usage and location of interest, material parameters, and stress intensity solution ($\alpha = K/\sigma$), 3. NDI inspection data)
b. Input data requirements: SHM data
    i. Boolean type of model with single or multiple zone data shall be available.
c. Input data uncertainties modeling
d. Risk requirement from MIL-STD-1530C
e. Computation tool: An existing computational tool will be used with stand alone augmented code to accommodate the additional SHM capability to solve the risk assessment problem, calculate the percentage of crack detected and repaired, and identify the optimal maintenance schedule.



** At the end of ith or the last usage interval, a NDI can be applied to detection the crack (as an option), this value was determined by the original RBDMS code without considering the SHM.

Figure 2. Risk Assessment Engineering Analysis Process with SHM Addition

Given the SHM Boolean capability plus the off-board data extracting design, it is impossible to monitor the crack all the time. Instead, the SHM should be performed at the pre-selected time intervals. In the following, the analysis procedure for SHM-based risk assessment process will be discussed in details:

1. With the addition of SHM, the current risk assessment process will not be changed drastically but it may increase the analysis iterations. Boeing's Risk-Based Design and Maintenance System (RBDMS) code will be used and integrated with additional SHM capabilities to perform the analysis. In general, data required for the analysis are essential the same except for the addition of SHM data. Based on this concept, the following analysis process was defined especially for the methodology to evaluate the POD for SHM and how to update the crack size distribution after performing a SHM inspection and repair.
    a. Perform the crack growth analysis up to the inspection time.
    b. Calculate the risk based on the same risk assessment process.
    c. Calculate the percentage of cracks detected and repaired based on the SHM's defined capability.
        i. For the SHM single-zone Boolean case:
            - Definitions for SHM single-zone Boolean case:
                a. aR = selected crack size for SHM singe-zone Boolean detection and repair. Note that crack sizes less than aR will be assumed not to be detected. (For this discussion a binomial variable is used, in subsequent detailed analysis presented later in this report a continuous distribution is assumed.)
                b. PExceed = crack size distribution with a > aR = Pr(a > aR)
                c. PD = Probability of detection for a > aR = SHM capability
            - % of cracks detected and repaired = PR = PD x PExceed
            - % of cracks detected and not repaired (with crack size larger than aR) = (1-PD) x PExceed
        ii. For SHM multiple-zones Boolean case:
            - Definitions for SHM multiple-zones Boolean case:
                a. Pexceed1 = Pr(a > a1)
                b. Pexceed2 = Pr(a > a2)
                c. Pexceed3 = Pr(a > a3)
                d. Note that a1 < a2 < a3
                e. Pexceed1 > Pexceed2 > Pexceed3
                f. Probability of detection should have the following condition: PD1 < PD2 < PD3. These data should be defined based on SHM capability.
            - % of cracks detected and repaired = PR = [0. x PExceed1] + PD1 x (PExceed1-PExceed2) + PD2 x (PExceed2 – PExceed3) + PD3 x PExceed3
            - % of cracks detected and not repaired = (1 - PD1) * (PExceed1 - PExceed2) + (1 - PD2) x (PExceed2 – PExceed3) + (1 - PD3) x PExceed3

- % of cracks detected and not repaired with crack size larger than a3 = (1 - PD3) x PExceed3

d. Update the crack size distribution by replacing % of cracks detected (= PR) with the repaired crack size distribution (usually considered equal to an initial flaw size distribution, i.e., as good as a new one) and merge with the original crack size distribution which has not been repaired.

i. For the SHM single-zone Boolean case:

- Based on the above definitions for the SHM single-zone Boolean case, the updated crack size distribution = (1 – PExceed) x (crack size distribution with a < aR – a truncated distribution) + PExceed x [{(1-PR) x (crack size distribution with a > aR – a truncated distribution)} + {(PR) x (repaired crack size distribution)].

ii. For the SHM multiple-zones Boolean case, the process may be more complicated than the single-zone case and a numerical process is required to establish the updated crack size distribution.

- Based on the above definitions for the SHM multiple-zones Boolean case, the updated crack size distribution = (1 – Pexceed1) x (crack size distribution with a < a1 – a truncated distribution) + (Pexceed1 - Pexceed2) x [(1- (Pexceed1-Pexceed2) x PD1) x (crack size distribution with a1 < a < a2 – a two-sided truncated distribution) + (Pexceed1-Pexceed2) x PD1 x (repair crack size distribution)] + (Pexceed2 - Pexceed3) x [(1- (Pexceed2-Pexceed3) x PD2) x (crack size distribution with a2 < a < a3 – a two-sided truncated distribution) + (Pexceed2-Pexceed3) x PD2 x (repair crack size distribution)] + (Pexceed3) x [(1- (Pexceed3) x PD3) x (crack size distribution with a > a3 – a one-sided truncated distribution) + Pexceed3 x PD3 x (repaired crack size distribution)].

e. Based on the updated crack size distribution, calculate the updated risk.

2. Based on the updated crack size distribution, perform crack growth to the next SHM inspection interval and repeat the above process from steps 1.a to 1.e. The process will then be repeated until the selected number of inspections has been reached. Note that this process should have an option to perform NDI POD inspection as well as the SHM inspection.

The above developed SHM-related strategy will be coded and completed in early May timeframe and an updated risk-based analysis code will be developed.

Step 2. Review identified technology shortcomings and gaps and develop necessary strategy to resolve these shortcomings and gaps.

This step will be complete after a thorough demonstration case has been solved. The following are extracted from the previous progress report to reiterate the identified shortcomings and gaps. It is anticipated that some of these may be resolved in the execution of this phase of the project.

1. For the proposed CBM+SI architecture, advanced risk assessment analysis strategy was used to deal with the uncertainties incurred from the complex crack growth model, loads, material strength, NDI and SHM data. It is important to have a robust strategy that will satisfy Air Force's requirements and identify the optimal maintenance schedule to save cost and improve aircraft's availability. The following questions come from the risk assessment analysis processes and tools development. Some resolutions or discussions are included for reference. Additional research and development to answer all of these questions are needed.
   a. How to update the crack size distribution?
   b. How to determine the next inspection interval?
   c. How to resolve the missed crack issue which deterministic approach has the most difficulty? This issue must be studied in detail and documented.

3.4 Perform CBM+SI Risk Analysis On Selected Beta Testing Cases

Step 1. Based on the collected data (1.1.2.3.1), modeled variables (1.1.2.3.2), proposed method and developed code (1.1.2.3.3), perform a CBM+SI risk assessment for the selected beta testing cases (1.1.1.4).

Perform a CBM+SI risk analysis based on the data acquired and calculate the risk that shall be used to compare with the ASIP's risk requirements in order to determine the optimal maintenance schedule. Since SHM's Boolean capabilities are currently in development, it is necessary to consider the following four maintenance options for the selected BH component:

1. Deterministic based approach: By calculating the corresponding risk based on the inspection intervals determined by using the deterministic approach, it is possible to compare with other options. In the past, the deterministic approach was based on the safety factor (= 2) but the actual risk remains unknown.
2. Risk based (1.E-7 requirement) with NDI inspection: This approach used the MIL-STD-1530C risk requirement of a Single Flight Probability of Failure (SFPOF) not to exceed 1.E-7 to determine the inspection schedule. At the time of inspection, NDI will be performed and % of cracks detected and repaired will be estimated.
3. SHM based from time zero: This approach uses the key advantage of SHM of easy access to inspect the component. Therefore, a preset time interval is used to determine the risk and perform inspection and repair, i.e, update the crack size distribution in the analysis. Potentially, a large number of inspections will be performed but as a result the risk will be reduced to the minimum.
4. Risk based for the first inspection and then SHM based: This approach is a combination of approaches 2 and 3. Based on approach 2's first inspection time determined by a SFPOF of 1.E-7, it will reduce the number of inspections during the initial phase of crack growth. After the first inspection, the remaining inspections are based on a pre-selected SHM inspection time interval.

Based on the data shown in Appendix A, the component 12B will be solved using the above four approaches and their results are shown as follow:

3.4.1 Deterministic Based Approach Results:

Since the damage tolerance life for the F-15 Bulkhead 12B location is equal to 1300 hours, the inspection interval becomes 1300/2 = 650 hours with consideration of a safety factor of 2. For the follow-on inspection interval, because the minimum identifiable crack size by NDI is equal to 0.05", the second (and follow-on) inspection interval was found equal to 650 hours with consideration of a safety factor of 2. Based on the same 650 hours inspection interval, a total of 18 inspections were considered.

The purpose of running this option is to check if the proposed inspection interval (650 hours) will accurately protect the safety of aircraft, i.e., a risk that less than 1.E-7. The SFPOF for the deterministic approach is plotted in Figure 3. The calculated SFPOF exceeded the risk threshold of 1.E-7 at 4550hours.

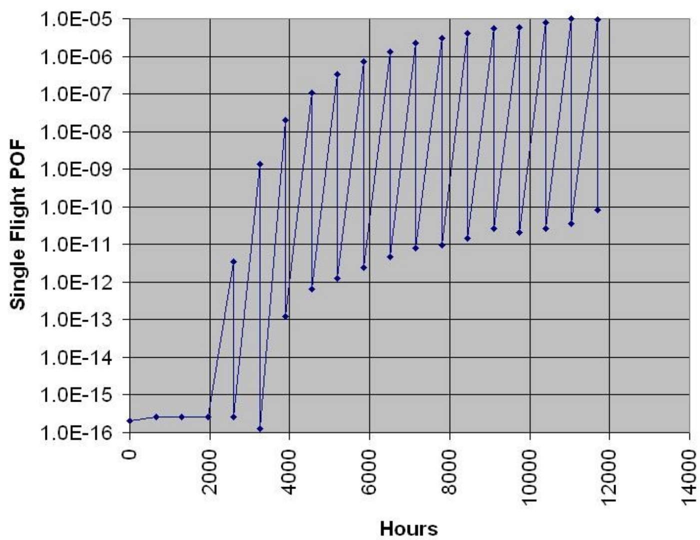


Figure 3. Single Flight Probability of Failure – Deterministic Approach

The percentage of cracks detected and repaired with each inspection, i.e., the portion of the original crack size distribution that is replaced with the repaired crack size distribution is shown in Figure 4. In addition, in these analyses, the POD is a continuous distribution and not the binomial value considered earlier.

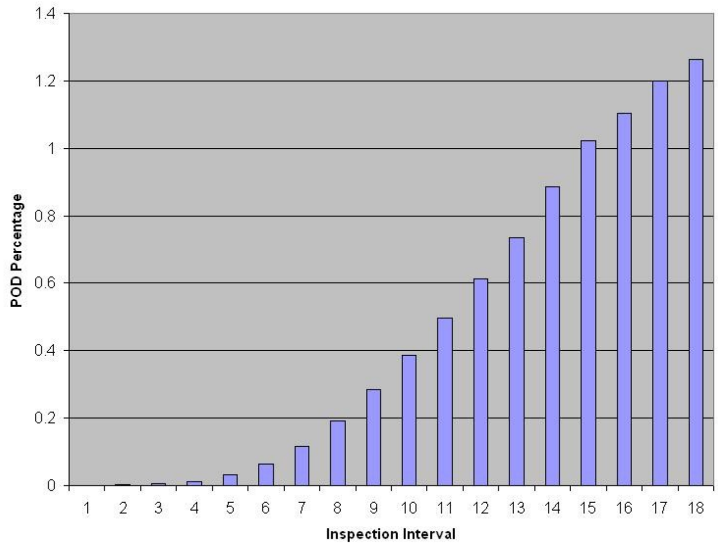


Figure 4. Percentage of Cracks Detected – Deterministic Approach

3.4.2 <u>Risk-based NDI Approach Results:</u>

This approach was based on the MIL-STD-1530C risk requirement of 1.E-7 to determine the inspection schedule. At the time of inspection, for this case, NDI will be performed and % of crack will be detected and repaired. The same strategy can be applied to apply SHM especially for the first inspection interval.

In the following, both the SFPOF and the percentage of crack detected are plotted in Figure 5 and 6, respectively.

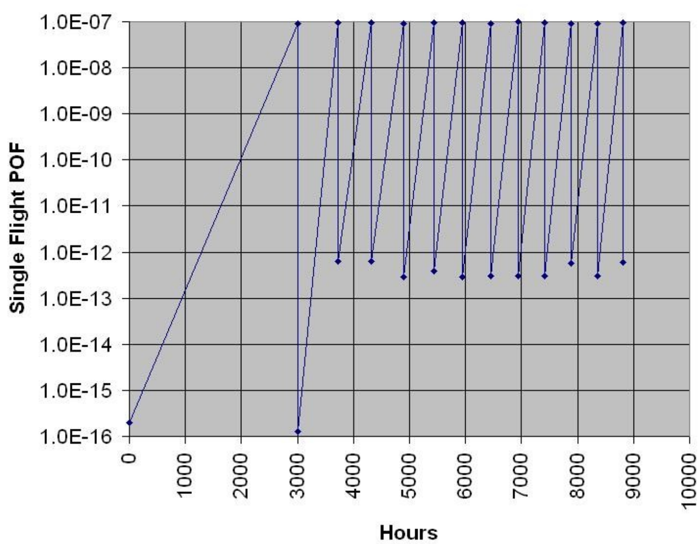


Figure 5. Single Flight Probability of Failure – Risk-based NDI Approach

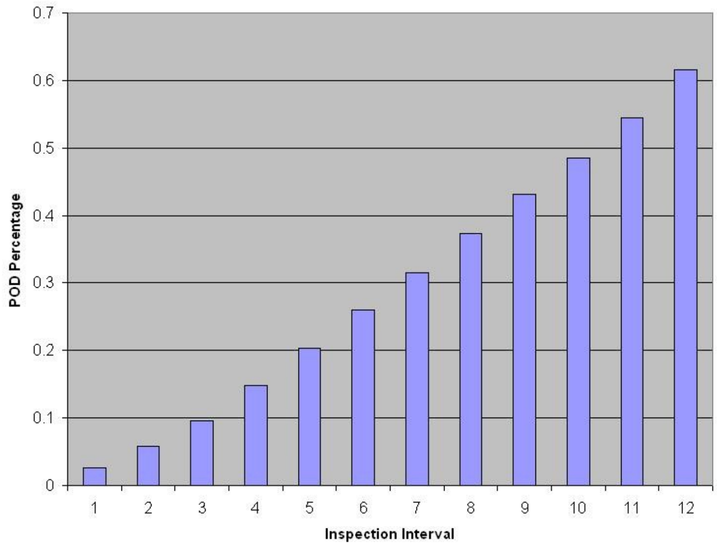


Figure 6. Percentage of Cracks Detected – Risk-based NDI Approach

3.4.3 SHM Based From Time Zero Approach Results:

This approach uses the key advantage of SHM in easy access to inspect the component so frequent inspection and repair can be done. However, due to current stand alone off-board SHM data analysis capability to monitor the component where all the time on functionality is not possible, a preset time interval is used to perform inspection and repair and at the same time calculating the corresponding risk. For this approach, potentially, a large number of inspections are required but the risk should be reduced to the minimum.

In the following, both the SFPOF and the percentage of crack detected are plotted in Figure 7 and 8, respectively.

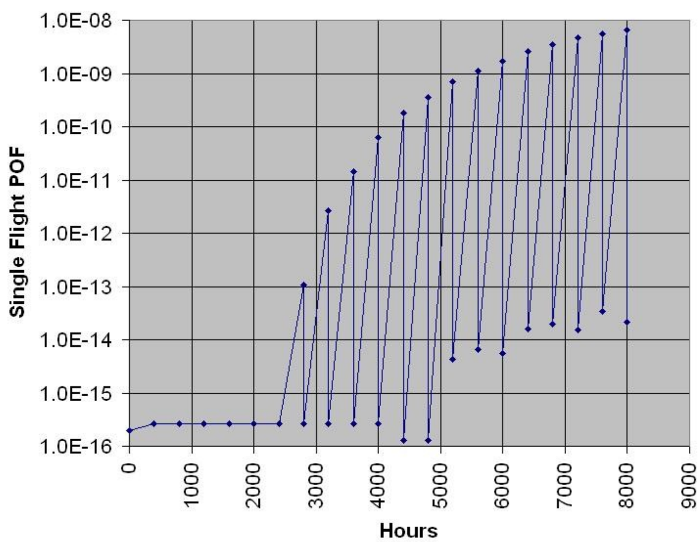


Figure 7. Single Flight Probability of Failure – SHM from Time Zero Approach

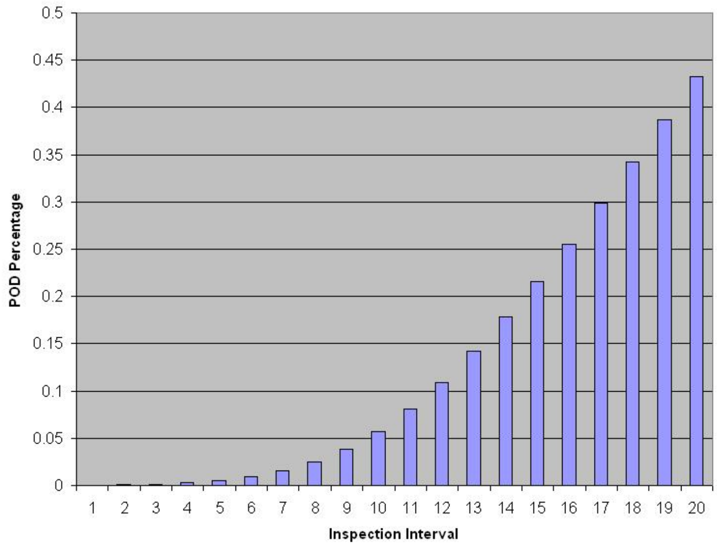


Figure 8. Percentage of Cracks Detected – SHM from Time Zero Approach

3.4.4 <u>Risk-Based for The First Inspection Approach Results:</u>

This approach is a combination of approaches 2 and 3. It is important to reduce the total number of inspections and repairs based on SHM approach. Based on approach 2's first inspection time (determined by risk of 1.E-7), it will greatly reduce the number of initial SHM inspections because the initial phase of crack growth will not have a lot of detections and repairs. After the first inspection, the remaining inspections are based on a pre-selected SHM inspection interval. Below, both the single flight probability of failure and the percentage of crack detected are plotted in Figure 9 and 10, respectively.

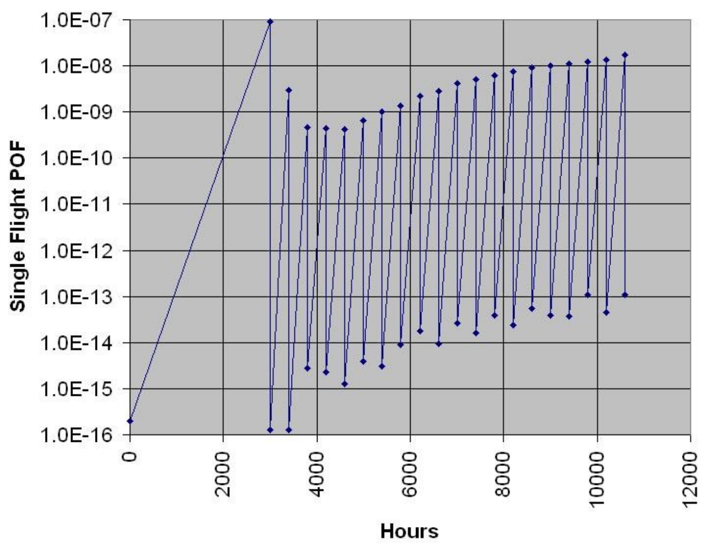


Figure 9. Single Flight Probability of Failure – Risk-based NDI Approach

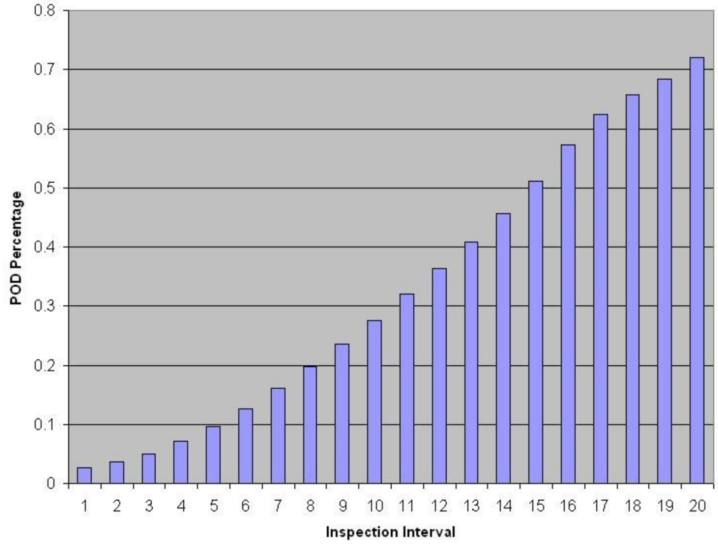


Figure 10. Percentage of Cracks Detected – Risk-based NDI Approach

3.5 Compare Results From Both CBM+SI and Deterministic Approaches

Step 1. Summarize the data and compare with the results obtained by using deterministic approach

As discussed earlier, the proposed CBM+SI strategy will apply a Boolean type of SHM to perform the inspection and repair. As the integration of the necessary code and the analysis of the SHM system POD are still in work for the purposes of this analysis it was assumed that the SHM system would have similar capability to the current NDI including expected POD. Four options have been run and shown in the previous subsection. The results of these four options are compared and shown in Table 1.

As shown in Table 1, all the key data have been summarized for comparison. Considering the total number of inspections required to reach 8815 flight hours, the deterministic based approach (Scenario # 1) used 14 inspections and the NDI-risk based approach (Scenario #2) used only 12. For the deterministic approach, at 4550 hours, the risk already exceeded 1.E-7 level and reached up to 5.4E-6. The risk-based approach was able to maintain the risk below 1.E-7. From this comparison, it shows the importance of quantitative information. For the deterministic based approach, even with the safety factor of 2, the outcome may be un-conservative, i.e., the SFPOF may exceed the 1.E-7 threshold.

Table 1. Results Comparison

	Deterministic Approach Scenario #1	NDI – Risk Based Approach Scenario #2	SHM – Risk Based Approach I Scenario #3	SHM – Risk Based Approach II Scenario #4
Inspection interval Determined?	Based on a safety factor of 2	Based on risk requirement of 1.E-7	Tight with routine insp. schedule for easy access	Based on risk requirement of 1.E-7 for the first insp.
Inspection interval hours	650	3000, 720, 590, 580, 540, 520, 500, 490, 480, 470, 465, 460	400 for all inspection intervals	3000 as the first one and then 400 for all inspection intervals
No. of inspection intervals to reach ~ 8815 hours	14	12	23	16
Risk level range	At 9100 hrs, max. risk = 5.47E-6; at 4550 hrs, the risk > 1.E-7 already	Maximum risk = 1.E-7.	Very small risk from the beginning to the 6.7E-9 at 8000 hrs.***	Max risk = 1.E-7 at 3000 hours and then reduced. At 9000, risk =1.E-8.***
% crack detected & repaired	At 9100 hours, 0.886% detected.	At 8815 hours, 0.616% detected.	At 8000 hours, 0.43% detected.***	At 9000 hours, 0.572% detected.***

The SHM approach from time zero (Scenario #3) used 23 inspections to reach 8815 hours and the risk stayed below 1.E-7. The highest risk level was found to be around 6.7E-9. For the last approach, by using the risk-based approach to be the first SHM inspection time, the total number of inspections was reduced from 23 to 16 and the risk level increased to 1.E-8, which is still below the 1.E-7 requirement. These two SHM related approaches definitely need to perform more inspections than the risk-based NDI approach but the risk level remains much smaller than the risk-based approach.

In addition to the number of inspections, the other key data to be recognized is the % of cracks detected and repaired. The risk-based approach uses fewer inspections, 12, in comparison to the SHM approaches which uses 23 and 16 inspections, respectively. The risk level of SHM approaches remain at a lower level than the risk-based approach, i.e., with each inspection the crack size distribution is updated after an inspection with new information that either no cracks were found, or cracks were detected and repaired so that a portion of the distribution was updated based on the repaired crack size distribution.

Based on the above data, it is very hard to determine which approach will be the most cost effective maintenance strategy. To perform the trade-off, a Technical Performance Measurement (TPM) model will be created to link with the above data. Then, the developed TPM model will be used to estimate the overall cost for each approach and the most cost effective, technically acceptable maintenance option identified. Additional discussion of the proposed TPM model can be seen in the TPM Measurement for Success section of this report.

Step 2. Identify potential shortcomings and gaps to be improved especially when applying the developed CBM+SI strategy to the fleet level (work with subtask 1.1.2.6 "Forward Looking Assessment").

Based on the proposed CBM+SI strategy and the demonstration example, potential shortcomings and gaps will be identified and summarized for further investigation and improvement.

4.0 Sensitivity Analysis

The objective of this task is to perform a series of sensitivity analyses to determine, which variables contribute the largest influence on the key technical performance measures. In addition an optimization approach will be developed which demonstrates how, given the definition of the key variables involved, an optimum maintenance plan can be created which minimizes cost and maximizes aircraft availability while maintaining acceptable risk levels. This task is schedule to start in August and be completed in September.

5.0 Measurement of Success via Technical Performance Measurements (TPM)

The objective of this task is to conduct the business case analysis on implementing CBM+SI solution for the demonstration system (Task 1.1.2.5) and show the impacts for the aircraft fleet. The business case will show the configurations' impacts on the fleet availability, labor hour usage, and total cost of ownership.

5.1 Establish the Baseline

Task 1.1.2.5.1 in the Statement of Work states, "Boeing shall populate the operational and cost benefit analysis models with the baseline system's utilization, reliability & maintainability, and cost data in order to define the baseline system for comparison to the CBM+SI solution's demonstrated benefits."

Historic maintainability and reliability data for the F-15C/D, covering operations from February 2004 to January 2009 were gathered from the Air Force Maintenance Operational Query System (MOQS) database. This historic reference was used to establish the baseline performance of the fleet. A key metric found in the database was the fleet's mission capable rate. For the purpose of this study, this mission capable metric was used as the baseline fleet availability, for the platforms will only be available when not in any kind of maintenance. This value was used to eventually calculate the elapsed downtime for all maintenance and to determine that portion for the lower bulkhead.

Although maintenance actions were recorded for the FS 626.9 bulkhead through Work Unit Code 11DAP, none of them had records covering the repairs on severe cracks in this bulkhead. Only two known cracks on this bulkhead occurred in the 1980s and 1990s, but data in the Air Force MOQS only cover from 2000 to 2009. Still, Boeing personnel provided insight on the occurrences and cost of these failures, and the maintenance actions and their labor hours covering this Work Unit Code were noted. A possibility may exist for a combined, reduced duration of all bulkhead repairs if their conditions are frequently monitored.

Also, data on the probabilities of bulkhead failure and detection of cracks were provided from the previously discussed risk analysis. Analyses were conducted on two F-15 Bulkhead critical locations: 12B and 237. At the time of this progress report, only the 12B zone was considered in the TPM model.

Using the historic reliability and maintainability data and the risk analysis, a baseline model was established. Models such as the System Health Operations Analysis Model (SHOAM) and the Probabilistic IVHM Cost-benefit Analysis Model (PICAM) were considered for TPM analysis; however, these modeling tools are better suited to analyze a series of implemented solutions. Because the focus is only on the lower bulkhead, a simpler model was created to calculate the TPMs. Although further analysis on the repairs for zones 12B and 237 were provided in an earlier section, only portions of that analysis became the basis for the model.

The following parameters and assumptions were established for the baseline model:

- Timeframe for the model: 25 years
- Number of F-15C/D in the fleet: 300

- Average flight hours per flight (based on the composite): 1.3 Hrs
- Average flight hours / plane / year: 275 Hrs
- Number of holes for 12B on the platform: 18
- Labor rate: $80/Hour
    - Estimated rate for any officer, calculated from AFI 65-503, Table A32-1, FY09
- Inflation rate: 3%
- Discount rate: 10.5%
- Unit platform cost: $25M
    - Cost for F-15E is approximately $59M from Janes.com, so a smaller value was used for the F-15C/D.
    - This cost is used to calculate the monetary equivalent for fleet availability change.
- Repairs on the bulkhead occur right after scheduled inspections.
- Time spent for repairs: 1.5 hours
- Cost for inspections and repairs are based solely on the labor hours.
- Failure cost has two possibilities:
    - Unit platform cost ($25M) to represent platform loss, or
    - Estimated cost for bulkhead repair based on past experience ($1M), which includes approximately 1500 labor hours and material costs.

5.2 Capture Solution Implementation Costs

From Task 1.1.2.5.2 in the Statement of Work, "Boeing shall capture the estimated development, production, and operating & support costs of the demonstration system in the cost benefit analysis model."

Technologies similar to the proposed CBM+SI alternatives were researched to estimate the resources and time needed for development, production, and installation on target platforms. A similar analysis on SHM benefits for the F-22 lug was conducted within the company, and a model from a fellow Boeing employee contained the estimated costs to develop and implement sensors onto a structure.

Below are the estimated costs in fiscal year (FY) 2009 dollars for developing and implementing a set of sensors to the 12B zone:

- Design Cost / Unit: $4,000
- Production Cost / Unit: $1,100
- Certification Cost / Unit: $4,000
- Physical Unit Cost: $500
- Installation Support Material Cost / Unit: $2,000
- Installation Labor Cost / Unit: 5 hours x Labor Rate

To cover the development, production, and installation of SHM solution, the following assumptions were established:

- Development and Certification of Solution: Years 0 (Current) and 1
- Production and Installation of Solution: Years 2 and 3

These costs for SHM approaches were entered to the TPM model, and the total costs of ownership between the baseline and modified configurations were compared.

5.3 Capture Solution Benefits

Task 1.1.2.5.3 in the Statement of Work states, "Boeing shall capture the demonstrated impact of CBM+SI on the system's reliability & maintainability metrics in the operational and cost benefit analysis models."

Four scenarios were analyzed to determine the operational and cost impacts in different configurations:

- #1: Deterministic (Baseline) Approach – Fixed inspection interval of 650 hours
- #2: NDI Risk Based Approach – Identify inspection intervals based on the risk threshold of 10^{-7}
- #3: SHM Approach I – Identify first inspection interval based on the risk threshold of 10^{-7}, and then use fixed inspection interval of 400 flight hours
- #4: SHM Approach II – Fixed inspection interval of 400 flight hours

The single flight probability of failure and the probability of crack detection for each of these scenarios are discussed in a previous section. Note that the risk probabilities after each flight for scenarios 2-4 are still significantly lower than the baseline approach. Also note that the implementation of the SHM solution will reduce the inspection time from 1.5 hours to 0.5 hours.

Only the SHM approaches are assumed to develop and implement technology to the platforms and ground operations. Scenario #2 was assumed to not add additional technology onto the platforms, for it simply meant identifying the next flight hour when the overall risk reached 10^{-7}. Meanwhile, the intervals are set in the SHM approaches, but gathering the data through on-board sensors and conducting analysis can reduce the risks of structural failure.

5.4 Determine Operational Benefit Analysis

Task 1.1.2.5.4 from the Statement of Work states, "Boeing shall utilize the discrete-event simulation operations analysis model to evaluate the baseline and CBM+SI enhanced system's operational metrics, i.e. availability. The delta operational benefit for CBM+SI shall be determined from this analysis."

The simple TPM model generated the fleet operational results for each scenario, shown in Table 2.

As expected, simply adding the SHM solution to cover only one structural area has minimal impact on the fleet's mission capable rate, but the downtimes for inspections and repairs and the number of expected failures are smaller than the deterministic approach. The failure quantity is based on summing all of the expected failures for each flight.

Table 2. Comparison of Performance Results for Each Scenario

	Deterministic Approach Scenario #1	NDI Risk Based Approach Scenario #2	SHM Approach I Scenario #3	SHM Approach II Scenario #4
Total Labor Hours	9089	6390	3103	4166
SHM Installation			1500	1500
Inspection	9000	6300	1500	2550
Repair	89	90	103	116
Change in Mission Capable Rate	baseline	0 %	+0.01 %	+0.01 %
Total Downtime (Hours)	9089	6390	1603	2666
Inspection	9000	6300	1500	2550
Repair	89	90	103	116
Expected Number of Repairs	59.2	59.8	68.9	77.5
Expected Number of Failures	0.318	0.096	0.042	0.001

5.5 Perform Cost Benefit Analysis

From Task 1.1.2.5.5 in the Statement of Work, "Boeing shall evaluate the cost benefit of the CBM+SI solution by using the operational benefit analysis results, in addition to the solution costs and benefits, captured in previous steps in the cost benefit analysis model. The results shall include the Net Present Value, Return on Investment, cash flow, and maintenance man-hours per flight hour."

The simple TPM model generated the fleet monetary results for each scenario in Table 3.

Table 3. Comparison of Cost Results for Each Scenario

	Deterministic Approach Scenario #1	NDI Risk Based Approach Scenario #2	SHM Approach I Scenario #3	SHM Approach II Scenario #4
SHM Prod. And Install Costs ($)			$ 3,728,176	$ 3,728,176
Expected Inspection Costs ($)	$ 1,078,761	$ 852,576	$ 202,561	$ 307,095
Expected Repair Costs ($)	$ 12,996	$ 13,047	$ 15,055	$ 17,170
Expected Fleet Equiv. Benefit ($)		$ 1,313	$ 3,642	$ 3,125
Expected Failure Costs ($) (When Failure Cost = $25M)	$ 11,747,761	$ 2,783,460	$ 1,023,712	$ 22,952
Expected Failure Costs ($) (When Failure Cost = $1M)	$ 469,910	$ 111,338	$ 40,948	$ 918

The formula for total cost of ownership when focusing on the lower bulkhead maintenance consists of the following:

Total Cost = [SHM Production and Installation Costs]
+ [Expected Inspection Costs]
+ [Expected Repair Costs]
+ [Expected Failure Costs]
– [Expected Fleet Equivalent Benefit]

While implementing one of the SHM approaches may show overall loss compared to the baseline, all scenarios do not yet account for additional material costs covering repairs and failures. Also, the maturity of the proposed technology can affect the costs to develop, certify, produce, and install the solution to the fleet.

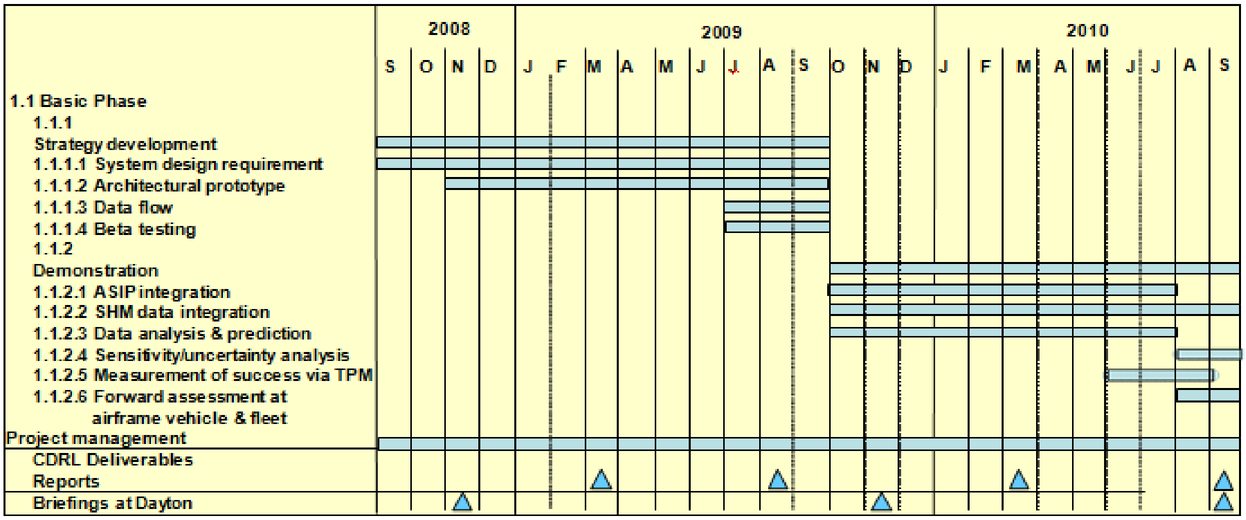
5.6 Next Steps

The TPM model will be adjusted to capture the costs for solution development and implementation, depending on the proposed technology's maturity. This model will also include the costs and benefits from inspecting additional zones such as Zone 237. As the baseline and proposed configurations are refined, the range of costs and benefits will be added to the model to determine the likely, minimum, and maximum impacts that can occur for the fleet.

6.0 Forward Looking Assessment

The objective of this task is to apply simple statistical and probabilistic analysis techniques to the methods and results obtained in the Demonstration in order to give some insight into how they may be used in the context of the follow-on of Phase II project as applied in the context of the aircraft system, and fleet. This task is scheduled to start in August and be completed in September.

Schedule



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Appendix A. Input Random Variables Data Summary

The current ASIP is ready to provide the basic required information to perform an effective risk assessment except for a probabilistic analysis strategy. These basic requirements are:

- Aircraft usage characterization: Loads and Environmental Spectra Survey (L/ESS) or Individual Aircraft Tracking (IAT) data
- Crack growth and residual strength based on demonstrated usage and location of interest, material parameters, and stress intensity solution ($\alpha = K/\sigma$)
- Inspection data: Crack size and usage hours at detection

With this data, by using proper uncertainties modeling strategy to convert the data into statistical distributions, a probabilistic risk assessment can be used to compute the risk and compare with the single flight probability of failure requirement stated in Mil-Std-1530C (Reference 1). With the proposed probabilistic risk assessment strategy, the safety factor associated with the existing deterministic approach can be "converted" into the risk and thus calibrated accordingly.

Based on the proposed risk assessment process, strategies for uncertainty modeling play an important role in estimating risk. Fracture toughness, maximum stress during a flight, and initial crack size are key contributors to the risk estimation. In addition, the parameters required for the NDI POD curve and repair crack size distribution are key contributors for risk mitigation purpose.

In the following subsections, a list of random variables required for the F-15 Bulkhead component (12B location) risk assessment is developed.

- Initial crack size distribution
- Repair crack size distribution
- Fracture toughness distribution
- Maximum stress distribution
- POD parameters

A.1 Initial Crack Size Distribution

For the F-15 Bulkhead component (12B location), the initial crack size distribution selected for the Titanium material Ti-6Al-4V is a Weibull distribution with Shape parameter and Scale parameter equal to 1.541 and 0.0022, respectively. This distribution was recommended by Mr. Chuck Babish, Air Force Life Cycle Management Center Technical Advisor, Aircraft Structural Integrity.

A.2 Repair Crack Size Distribution

In general, the repair crack size distribution was considered equal to the initial crack size distribution because it is assumed the repair quality is good so the quality of the crack size distribution should be as good as new.

A.3 Fracture Toughness (Kc) Normal Distribution

Without actual data, normal distributions with the coefficient of variation (μ/σ) from about 3% to 10% for aluminum and titanium alloys and most steels are used to model the Kc distribution. For this Titanium material Ti-6Al-4V, the mean value equals to 100.2 and the standard deviation equal to 10 were assumed, i.e., a 10% COV was assumed for conservatism.

A.4 Maximum Stress Gumbel Distribution

As discussed in the input data requirement subsection, the methodology to determine the distribution of the maximum stress Gumbel distribution had been discussed in details. Based on the procedure proposed by the PROF code, the maximum stress Gumbel distribution was calculated using the load exceedance data and a least square fit was used to determine the Gumble EVD. As shown in Figure A-1, three different least square fit curves were plotted for comparison. For conservatism, an 8-points fit (with Scale (Asig) = 0.0468 and Location (Bsig) = 0.97) was selected for the Gumble EVD.

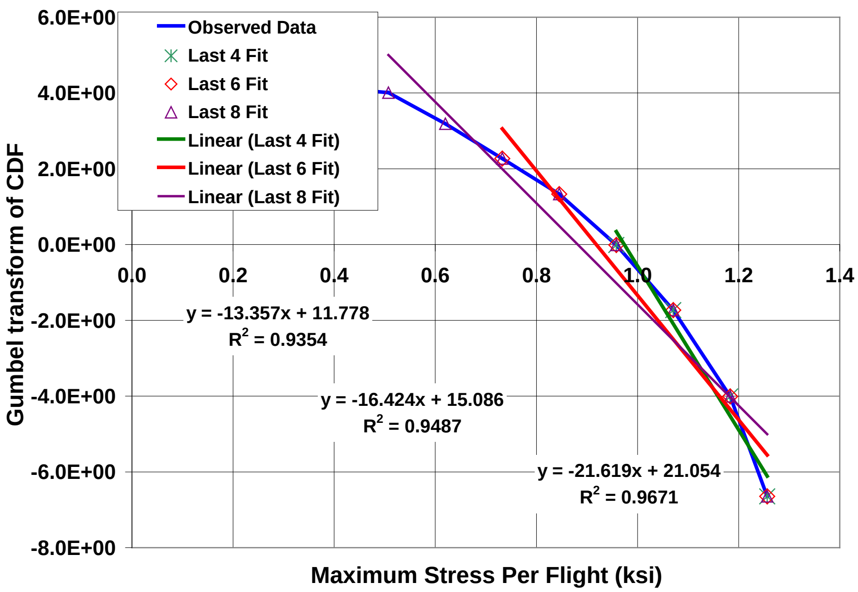

Figure A-1. Least Squares Fit to Stress Exceedances

A.5 Probability Of Detection (POD) Parameters

To model the probabilities of detection (POD) curves, the crack size that can be detected with 90% detection and 95% confidence level must first be identified. For the 12B location, a bolt hole eddy current inspection method will be used to inspect the component. Based on this method, the 90% detection and 95% confidence level was found equal to 0.05 inches. In addition to this value, the median value with a 50% detection and 95% confidence level was found at 0.025 inches. With these two values, it is possible to establish a lognormal POD model, Figure A-2, with the following parameters:

- amed (median value of X) = 0.025
- asteep = 0.5
- amin (minimum value of X) = 0.003 inches
- and Probability Of Inspection (POI) = 1

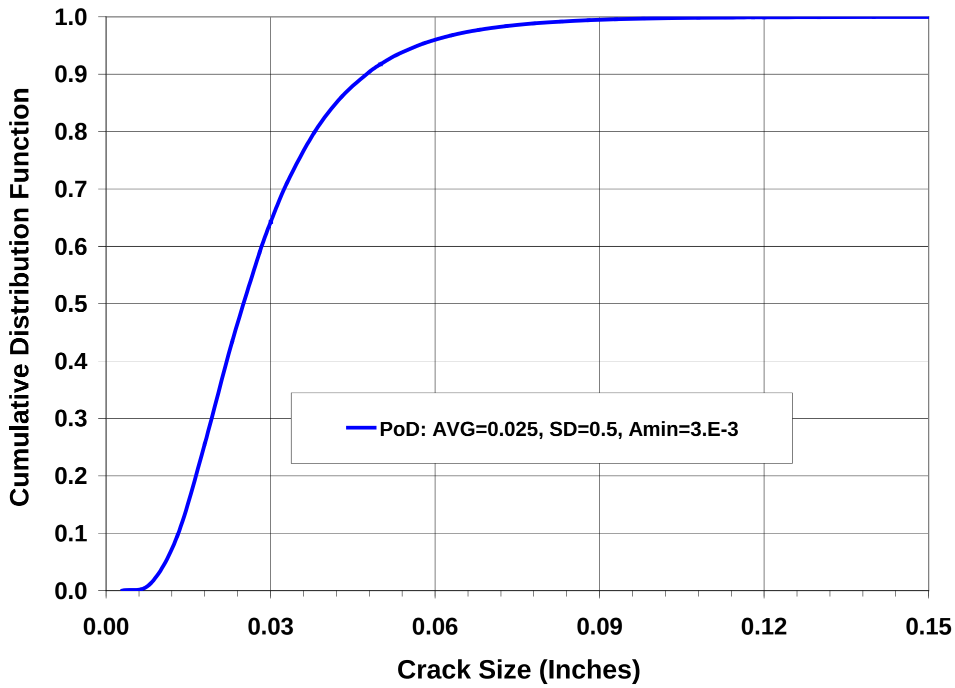

Figure A-2. Probability of Detection Curve

A.6 Important Deterministic Input Data

Crack Growth Curve (Crack Size a (inches) vs. Flight Hours T) – the same deterministic Damage Tolerance Analysis (DTA) results will be used to perform the growth of fatigue cracks by projecting the percentiles of the fatigue crack size distribution.

Geometry (Crack Size a (inches) vs. K/sigma) – Under current Air Force regulations, damage tolerance analyses are performed for every critical location on an airframe. As part of these analyses, the stress intensity factor geometry correction, β(a) , for correlating stress, loading condition, global geometry, and crack size will have been determined. The geometry file also plays an important role when computing the risk as shown in the following failure mode or limit state function:

$$g = \frac{K_c}{\beta\sqrt{\pi a}} - \sigma_{max}$$

The other key failure mode occurs when the crack grows to exceed the critical crack length as shown in the following limit state function:

$$g = a - a_{cr}$$

For interval probability of failure, the following data are important:

- Similar locations in an aircraft = 28
- No. of aircraft in a fleet = 300
- Average hours per flight = 1.3 hours.